VERTICAL OCEAN LOADING AMPLITUDES FROM VLBI MEASUREMENTS

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Abstract, Vertical ocean loading amplitudes are determined by analysis of IRIS geodetic VLBI data. The 4 nearly diurnal (K_1, P_1, O_1, Q_1) and 4 nearly semidiurnal $(K_2, S_2, M_2$, and $N_2)$ component amplitudes can be inferred from the data with accuracies of 1-2 mm. Uncertainties of total displacements can thus approach 1 cm. Empirically determined total displacements are considerably larger than the values calculated from two geophysical models. The Scherneck model is found to give a better representation of VLBI delay data than the model of Pagiatakis by about 3 mm in residuals at 6 sites. Empirical estimation of the ocean loading amplitudes reduces the IRIS VLBI fit χ^2 by 3067 for the 96 additional degrees of freedom, and reduces the residuals by 3 mm relative to a fit using the fixed Scherneck model. Vertical ocean loading amplitudes can thus be inferred from VLBI data at a level which improves the overall model, but detailed assessment of individual tidal components is presently obscured by inadequacies in modeling other tidal effects.

Introduction

Displacements of the Earth's crust by the time-varying distribution of ocean water ("ocean loading") can have peak-to-peak amplitudes as large as 3 crn even at points far removed from coastlines. These displacements occur at the ocean tidal frequencies, with approximately diurnal and semidiurnal periods. As sub-centimeter geodesy is approached, modeling of ocean loading is becoming an increasingly important error source. During the past decade, several workers [e.g. Pagiatakis *et al.*, 1982, Pagiatakis, 1990, Scherneck, 1983, 1991] have calculated the ocean loading effects at locations used for space geodetic measurements (Very Long Baseline Interferometry [VLBI], satellite and lunar laser ranging [SLR, LLR], and Global Positioning System [G PS]). Both Scherneck and Pagiatakis attempt to produce geophysical models of ocean loading that are valid at the millimeter level. Their models differ in dct ails of the Earth's viscoelastic response that arc considered in order to compute the loading Green's functions, aa well as in treatment of mass conservation and regional effects for global ocean tides. Scant empirical evidence exists to assess the two models, however, which can differ by 1 cm or more in instantaneous displacements. Effects of ocean tides play an important role in recent attempts to extend the accuracy of Earth modeling to the sub-centimeter level. Uncertainty in the ocean loading displacements of the observing stations was found to be an important source of systematic error in determinations of diurnal and semidiurnal UT1 and polar motion amplitudes [Severs *et* al,, 1992]. This paper explores the possibility of inferring ocean loading amplitudes from VLBI data, with the dual purposes of testing the theoretical predictions and providing empirical improvements to the models of space geodetic observable.

Ocean Loading

Displacements at an arbitrary site on the Earth's surface due to ocean loading are considered in a local coordinate system. In a vertical, North-South, East-West ($i = 1,3$) local Cartesian coordinate system at time t, the displacements δ_i can be expressed as

$$\delta_i = \sum_{j=1}^{N} A_{ij} \cos(\omega_j t + V_j(t) - \phi_{ij}) \qquad (1)$$

The two quantities ω_j and V_j(frequency and "astronomical argument" of tidal constituent j) depend solely on the Solar System ephemerides. The algorithm of Goad (McCarthy, 1992) is used to calculate these two quantities. On the other hand the amplitude A_{ij} and Greenwich phase lag ϕ_{ij} of each tidal component j vary with the response of the Earth. They can be derived either from particular models assumed for the deformation of the Earth, or from empirical data analysis. The eight major nearly diurnal and semidiurnal components (j) are, in standard notation: K_2, S_2, M_2, and N_2(with periods close to 12 h), K_1, P_1, O_1, Q_1 (periods close to 24 h). Three longer-period components, M_f (14 day), M_m (monthly), and S_{sa} (semiannual), are not included in this initial study, since the models predict their amplitudes to be smaller than 0.1 mm. Scherneck (1991) has calculated both vertical and horizontal displacements and phases for all the above-mentioned tidal components (A_{ij}, ϕ_{ij}). Pagiatakis (1990) considers only six tidal components (omitting K_2, Q_1, and the long-period terms).

Table 1 gives the vertical ocean loading amplitudes and phases calculated by Scherneck (1991) [see also the IERS Standards, McCarthy (1992)] for the six stations that are the most frequent participants in the IRIS [Carter *et al.*, 1985] VLBI experiments during the period 1984-92. The horizontal (N-S and E-W) components are not considered here. For the six IRIS stations, these amplitudes (when all in phase) range from 40% to 80% of the vertical amplitude, for both the Scherneck (S) and Pagiatakis (P) models. Long-term RMS displacements (equal to 1/2 the sum of squares of the amplitudes) range from only 27% to 56% of those in the vertical direction. While the horizontal components are thus not negligible, the vertical components are dominant, and for this initial study it was decided to consider only the vertical ocean loading station displacements.

Another reason for not estimating the horizontal components in this exploratory study is related to parameter degeneracies. Certain linear combinations of the ocean loading displacements δ_i for the set of stations participating in each experiment are equivalent to rotations and/or translations of either the station set or of the terrestrial reference frame. Such rotations are identical to rotations that are customarily described by UT1 and polar motion (UTPM) parameters at the ocean tidal frequencies. Until a method for treating these potential degeneracies is established, estimating all three components of the station ocean loading displacements can lead to ambiguous results. This paper thus focuses solely on the vertical displacements δ_i, the estimates of which are of course themselves partially susceptible to contributions from other nearly diurnal and semidiurnal unmodeled effects (e.g., solid Earth tides, atmospheric loading, antenna thermal expansion).

To permit linear parameter estimation, Eq. (1) is rewritten in terms of cosine and sine amplitudes as

$$\delta_i = \sum_{j=1}^{N} \left[A_{Cij} \cos(\omega_j t + V_j(t)) + A_{Sij} \sin(\omega_j t + V_j(t)) \right] \tag{2}$$

It is the coefficients A_C and A_S which are estimated and then transformed back to the A_{ij} and ϕ_{ij} of Eq. (1).

Data and Analysis

One of the most uniform VLBI data sets collected during the past decade is that of the IRIS (International Radio Interferometric Surveying) project of the National Geodetic Survey (e.g. Fallen and Dillinger, 1992). It includes data from several stations in North America and Europe, situated at a variety of distances from coastlines, and was therefore considered suitable for an initial assessment of the feasibility of determining ocean loading displacements. The present study utilizes the IRIS observations from 24-h sessions carried out every 5 to 7 days during 1984 to late 1992, which total approximately 270,000 delay and delay rate pairs. Vertical ocean loading displacements are estimated for the six stations mentioned in the previous section. The number of observations that each station participates in is distributed as follows (in thousands): Westford== 155, Wettzell= 120, Richmond=100, Ft. Davis= 70, Mojave= 65, and Onsala=20. With the exception of the Fort Davis, Texas station (observing until early 1990) and the California station Mojave (which began regular observations in mid-1989), the data are uniformly distributed over the 9-year span. The Swedish station Onsala only participates in IRIS experiments once per month, which accounts for the relatively small number of Onsala observations,

A global linearized least-squares fit is used to estimate a large number of model parameters using the JPL software package MODEST [Severs, 1991], which was extended to permit estimation of ocean loading amplitudes, Modeling of the observable adheres to the 1992 IERS standards [McCarthy, 1992], with certain exceptions. One exception is ocean loading, for which only the horizontal amplitudes and phases are fixed at the Scherneck values specified by the IERS standards, while the vertical components of all stations are estimated, Another is the precession-nut ation model. Instead of the 1980 IAU nut ation series, we use the ZMOA- 1990-2 model [Herring, 1991], with a correction to the precession constant that was derived by Severs *et al.* (1992) in a study of ocean tidal UTPM effects. The ZMOA-1990-2 series is known to correct most of the defects in 1980 IAU to well below the mill iarcsecond level. Global diurnal and semidiurnal ocean tidal effects (variations of UTPM) are described with the model of Severs *et* al. (1992). The NUVEL-1 no-net-rotation model of plate motion [Argus and Gordon, 1991] is used to describe the time dependence of station coordinates. The reference station coordinates are fixed at their ITRF91 [Boucher *et al.,* 1992] values; all other station coordinates are estimated. The origin of celestial co-ordinates was fixed by adopting fixed values for a triplet of nearly orthogonal coordinates of the sources CTD 20 and OJ 287 (Steppe *et al.,* 1992); all other source coordinates are estimated. Behavior of the station clocks was modeled as a piecewise linear function of time, typically with several breaks during each 24 hour observing session. Tropospheric delays were mapped from zenith to the elevation angle of each observation with the map ping function of Lanyi (1984). A new (piecewise constant) zenith delay was estimated at each station at 3 hour intervals. With the exception of nearly diurnal unmodeled effects that depend on meteorological conditions, most aspects of the model outlined above are not expected to produce significant systematic errors in ocean loading amplitudes. The importance of correlations between vertical and horizontal ocean loading displacements was tested by increasing all horizontal amplitudes by 10%. This resulted in 1 – 15% (0.2 to 0.4 mm) shifts in the estimated vertical amplitudes.

Weighting of the observable is diagonal, with each weight being inversely proportional to the square of the observable error. Baseline-specific variable errors are root-sum squared with the observable errors, and adjusted in order to make the normalized chi-square for each session close to 1.0. The adjustable portion of the additional error for delays is normally <100 picosecond, and typically some tens of pa for all the IRIS data considered here.

The ocean loading parameters of interest here are the eight pairs of amplitudes A_{C1j}, A_{S1j} for the vertical displacements δ_1 at each observing station. For comparison with the geophysical models, Eq. (2) is transformed back to the form of Eq. (l):

$$\delta_1 = \sum_{j=1}^{N} A'_{1j} \cos(\omega_j t + V_j(t) - \phi'_{1j}) \tag{3}$$

with the amplitudes A'_{1j} and phases ϕ'_{1j} related to the estimated cosine and sine amplitudes via $A'_{1j} = (A^2_{Cij} + A^2_{Sij})^{1/2}$ and ϕ'_{1j} = $\arctan(A_{Sij}/A_{Cij})$.

Results and Discussion

Initial assessment of the significance of the vertical ocean loading amplitudes estimated from VLBI data is made by examining the RMS residuals for the observable. When the vertical amplitudes are estimated, in cent rast to being fixed at the Scherneck values given in the IERS standards, the overall RMS delay residuals are reduced by 3 mm in quadrature, The total χ^2 decreases by 3067 for the additional 96 degrees of freedom (16 ocean loading components for 6 stations) from its value of s229,000, which indicates a $\gg$99% confidence level that the adjusted values of these additional parameters better represent the physical model.

Table 2 reports the results for 8 vertical ocean loading amplitudes and phases for the 6 stations with the most data from a fit to all 270,000 IRIS VLB1 observations. These results are directly comparable to the Scherneck model of Table 1. The errors in Table 2 are formal statistical uncertainties resulting from linear least-squares parameter estimation. They range from 0.4 to 0.9 mm at semidiurnal frequencies, and from 0.5 to 1.4 mm at diurnal frequencies, with the largest values occurring for Onsala, the station with fewest observations. Based on the formal uncertainties, many shifts from the Scherneck amplitudes are highly significant, ranging up to $\approx 13\sigma$ for M_2 of Westford. The distribution of shifts is significantly skewed, with only 10 of 48 being negative, and peaks at $\approx$1.4 mm. With the exception of Westford, the long-term average ocean loading displacements given by the empirical model of Table 2 are substantially larger than those of the S or P models. In the extreme case of Onsala, this amounts to nearly a factor of 3.

The formal uncertainties do not represent the true errors because unmodeled noise had to be added to reduce the χ^2s to 1. The major factor in mismodeling errors is the neglect of tropospheric fluctuations. It is known that improved modeling of the troposphere either by accounting for correlations among observations based on a turbulence model, estimating more frequent zenith delays, or stochastic modeling can eliminate the need for added unmodeled noise (Treuhaft and Lowe, 1991). One of these methods will be employed in future extensions of this work. For the present, the effect was part] y assessed by repeating the fit with a small subset of the data ($\approx$1 month, *3000* observations) and tripling the number of troposphere breaks. The formal uncertainties of the vertical ocean loading amplitudes increased by 10-20%.

Another, more empirical method of assessing true errors was employed. The data set was partitioned into 6 subsets, each cent aining approximately 50000 observations (1984-5, 86-87, 88-89, 90, 91, and 1992), and identical fits were performed for each part. The standard deviation of the weighted mean of the six determinations is reported in Table 3 for all vertical ocean loading amplitudes and phases. These standard deviations of the results for the six data subsets are approximately twice the formal uncertainties of Table 2. The amplitude standard deviations are as large as 4.0 mm (P_1 for Ft. Davis), and the phase values range up to 64° (Q_1 for Ft. Davis). The distribution of amplitude standard deviations peaks near 1 mm, the median being just >1 mm, and the RMS scatter is 1.5 mm. The phase values are more uniformly distributed, with the peak, median, and RMS all being close to 40°. Similar statistics of the 48 amplitude and phase formal uncertainties show that the formal RMS us are 0.7 mm for amplitudes and 29° for phases. The standard deviations of Table 3 exceed the formal σs by a factor of 1.9 on average. Exclusive of other systematic errors, they are the best presently available estimates of the true accuracies of the results.

The long-term average Scherneck (S) and Pagiatakis (P) vertical amplitudes differ by only 0.7 mm RMS, but the resulting station displacement differences were seen to affect parameter estimates (Severs *et* 01., 1992). In fitting VLB1 delays, the S model shows an improvement of residuals over the P model by 3 mm in quadrature. Both models give residuals differing by 2 mm from a fit in which no ocean loading is modeled, with S being better and P worse than the null case. As mentioned before, estimating the vertical amplitudes produces a further improvement of 3 mm over the Scherneck model.

The present estimates of vertical ocean loading displacements differ from Scherneck by 3.1 mm (RMS) in long-term averages. These differences range from –0,5 mm for Westford to +6.3 mm for Mojave. The true accuracies are difficult to quantify, but even at the formal uncertainty level of 0.7 mm, they are nearly comparable to the differences with the S or P models. In fact, at the formal uncertainty level, the present empirical results just surpass the 99% confidence level for significant differences from *zero* displacement. Unlike global ocean tidal Earth orientation effects, these local effects can thus presently be inferred from VLBI data at a level that is only marginally useful in improving Earth modeling for space geodesy.

Conclusions

Amplitudes of the vertical component of ocean loading displacements at eight nearly diurnal and semidiurnal frequencies can be derived from VLBI observations. Their formal statistical uncertainties range from 0.4 to 1.4 mm, but the true errors are probably larger by at least a factor of 2. For the six IRIS stations considered here, the empirical results yield long-term average total displacements that are considerably larger than those predicted by the Scherneck (1991) and Pagiatakis (1990) theoretical models, and also show that VLBI data are capable of distinguishing between the models. Unfortunately, the sensitivity of the VLBI data does not appear to be high enough to permit empirical determination of the individual vertical amplitudes to considerably better than 1 mm at diurnal and semidiurnal tidal frequencies, which is required for discriminating fine details between the two models. When and if VLBI sensitivity reaches the sub-mm level, further complications in analyses will have to be faced. These include the separation of ocean loading displacements from other nearly diurnal and semidiurnal phenomena, as well as degeneracies between horizontal components of station displacements and global rotations.

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Table 1. A Priori Vertical Ocean Loading Amplitudes (mm) and Phases (degrees)

Term	Ft. Davis	Mojave	Onsala	Richmond	Westford	Wettzell
$(A, \phi)\, K_2$	0.4, 248	0.5, 273	0.2, 326	0.6, 191	0.8, 202	0.3, 324
S_2	1.5, 232	1.5, 249	0.9, 314	2.5, 198	2.8, 209	1.4, 322
M_2	1.1, 182	2.0, 351	3.8, 304	8.7, 167	10.2, 185	4.9, 291
N_2	0.5, 296	1.1, 307	0.8, 269	1.4, 147	2.2, 168	1.0, 273
$(A, \phi)\, K_1$	4.7, 33	9.8, 44	2.2, 316	1.9, 17	4.0, 355	1.8, 302
P_1	1.5, 31	3.1, 43	0.7, 310	0.6, 15	1.3, 356	0.6, 300
O_1	3.2, 18	6,2, 29	1.2, 237	1.4, 26	2.7, 356	0.8, 259
Q_1	0.6, 11	1.2, 21	0.0, 178	0.3, 37	0.6, 358	0.0, 248

Table 2. Vertical Ocean Loading Amplitudes (mm) and Phases (degrees) Estimated From VLBI Data

Term	Ft. Davis	Mojave	Onsala	Richmond	Westford	Wettzell
A' K_2	2.0± 0.6	2.4±0.5	0.8± 0.9	3.3±0.5	1.8± 0.4	0.6± 0.4
S_2	5.4 0.5	7.1 0.5	2.0 0.7	2.9 0.5	1.5 0.4	1.5 0.4
M_2	2.5 0.5	1.0 0.5	4.7 0.8	3.3 0.5	5.2 0.4	4.6 0.4
N_2	2.4 0.5	2.2 0.5	1.2 0.8	1.4 0.5	1.8 0.4	0.6 0.4
A' K_1	6.2± 1.0	17.7±0.8	3.1± 1.3	8.5±0.8	8.750.5	3.4± 0.7
P_1	6.5 0.9	2.5 0.8	8.9 1.2	2.7 0.8	3.7 0.5	5.0 0.6
O_1	4.8 1.0	7.6 0.8	5.8 1.3	3.0 0.8	1.6 0.5	0.7 0.6
Q_1	2.0 1.0	3.1 0.8	1.6 1.4	3.9 0.8	1.6 0.5	0.6 0.6
4' K_2	283± 19	316± 14	107± 48	110± 9	198± 21	271± 49
S_2	36 4	142 4	108 15	302 6	179 12	21 16
M_2	136 16	19 23	326 23	162 10	172 4	316 11
N_2	153 11	193 10	255 111	172 43	176 43	195 21
4' K_1	350± 14	33± 6	270± 35	31± 7	28± 5	348± 16
P_1	64 10	335 14	134 8	30 20	353 12	162 6
O_1	2 29	27 33	18 11	104 15	17 22	189 42
Q_1	213 23	285 14	68 51	74 13	293 21	304 66

Table 3. Standard Deviation of the Mean of Six Determinations of

Vertical Ocean Loading Amplitudes (mm) and Phases (degrees)

Term	Ft. Davis	Mojave	Onsala	Richmond	Westford	Wettzell
$(\sigma_{A'}, \sigma_{\phi'})\ K_2$	1.2, 53	0.5, 35	2.2, 43	0.5, 44	0.5, 60	0.6, 43
S_2	1.5, 26	0.9, 12	1.3; 50	1.0, 14	1.5, 44	1.0, 33
M_2	0.7, 33	0.6, 46	1.5, 18	0.7, 45	1.0, 59	0.7, 17
N_2	0.5, 43	1.2, 62	1.3, 36	0.2, 50	0.3, 44	0.4, 43
$(\sigma_{A'}, \sigma_{\phi'})\ K_1$	*2.0, 12*	*3.6,* 10	2.1, 36	1.6, 21	1.5, 12	1.7, 32
P_1	*4.0,* 11	1.7, 46	2.7, 52	2.2, 25	0.8, 30	1.9, 50
O_1	1.5, 29	1.1, 21	1.7, 32	0.5, 47	0.6, 32	0.9, 46
Q_1	*2.4, 64*	*0.4, 59*	*2.8, 30*	*0.8, 44*	1.1, *25*	*0.8, 32*